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RADIOGRAPHIC APPLICATIONS OF SPATIAL FREQUENCY MULTIPLEXING

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16. Abstract <p>A system was studied for encoding x-ray energy information onto photographic film. A variety of configurations were considered using different grating approaches. Those systems using gratings of selected materials represented severe constructional problems. The translated opaque grating, however, gave excellent results using phantoms and animals. A system was conceived and tested, using an optical grating, which provides significantly improved resolution.</p>			
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PREFACE

The objective of this project was the study of systems for encoding x-ray energy information onto photographic film. This information is then decoded and used to make clinically significant images of specific materials.

The scope of the work included the modification of a scanner for accepting radiographic film. An x-ray encoding system was designed and implemented using phantoms and animals. Detailed analytic studies were conducted on the optimum configurations.

Conclusions and recommendations are presented at the end of the report.

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INTRODUCTION

This project has been the subject of many published papers. As a result, this final report will make extensive use of these in the form of appendices.

The objective of this program was the study of the application of spatial frequency encoding techniques to radiography. In general, these techniques allow additional information to be encoded on a conventional radiograph so as to improve its diagnostic quality. The additional information being encoded represents different regions of the x-ray energy spectrum. This data, when decoded, provides information about specific materials in the body.

The basic system is described in Appendix A, "Selective Material X-Ray Imaging Using Spatial Frequency Multiplexing."

CLINICAL CONSIDERATIONS

There are a variety of significant problems in diagnostic radiology which are profoundly improved by selective material imaging. These include chest imaging, intravenous visualization of blood vessels and the intravenous pyelogram for visualizing lesions of the kidneys.

Chest imaging represents, by far, the most widely used modality in radiography. Because of its relatively low dose (< 50 mrad) and high information content, it is the only radiographic study which is performed asymptotically. Unfortunately, present chest imaging exhibits a relatively high number of missed lesions; approximately 30%. These are various tumors and infections which are found in retrospective studies after the disease has advanced. The bulk of these missed lesions can be

attributed to overlying structures, primarily bone. Thus, when bone is removed using selective material imaging, the tumors and other lesions underlying bone become visible and are diagnosed in early stages.

In addition, contrast enhancement of chest images is presently limited by the large dynamic range of all of the tissue. A tissue-only image with the bone removed allows significant contrast enhancement which is otherwise unavailable, greatly enhancing the subtle lesions.

Blood vessels are presently visualized using large amounts of iodinated contrast material. These are administered using a highly invasive procedure involving the surgical insertion of a catheter. As a result these tests are reserved for patients who have already experienced severe symptoms. Unfortunately, at this point the disease process is often irreversible. This includes heart disease where the occluded coronary arteries cause myocardial infarctions, the number one killer in the country. Another significant area are strokes and other cerebral diseases caused by occluding of the carotid arteries leading to the brain.

In this program, attempts are made to visualize these vessels noninvasively using selective material imaging. The iodinated contrast agent is injected intravenously in a non-invasive fashion. The resultant concentration of iodine in vessels is about two orders of magnitude lower than in the invasive catheter studies. As a result, the vessels are completely invisible in conventional radiographic studies. In selective material imaging, however, spectral energy information is used to make isolated images of iodine. With the intervening tissue removed, the vessels become visible using the non-invasive procedure. This offers the exciting prospect of screening studies for imaging

important vessels.

Kidney studies using the intravenous pyelogram or IVP are usually plagued with intervening bowel gas which significantly limits the visualization of kidney disease. In selective material imaging the soft tissue structures are eliminated, thus removing the contrast of the bowel gas. The resultant images provide remarkably improved visualization of kidney disease.

EXPERIMENTAL STUDIES

The primary experimental study involved the encoding and decoding of x-ray images at different energies and processing this data to produce images of specific materials. For encoding, a variety of lead gratings were fabricated. These were placed against a film-screen cassette and translated between exposures at different energy spectra. Thus the encoded information appeared on a spatial frequency carrier.

For decoding, a drum scanner system was modified to accept radiographic transparencies. A system of decoding electronics was designed and fabricated for isolating the modulated envelope and the average value of the signal. These signals were then processed in various linear and nonlinear sub-systems to provide the desired signal. The resultant decoded and processed signal is used to modulate a light emitting diode to produce an image on film mounted on a synchronously rotating drum.

This experimental setup was used to produce isolated images of iodine using phantoms and animals. Images were acquired on either side of the iodine K edge using narrow band x-ray filters. These were then

scanned and processed to produce isolated iodine images. Special compensation was used to compensate for the non-ideal energy spectra. These results are described in Appendix B, "Isolated Iodine Images Using Spatial Frequency Encoding."

The system described above required the mechanical translation of the grating between exposures. Studies were also conducted using special gratings consisting of alternate lines of different materials. This would allow encoding in a "snapshot" fashion without requiring grating translation between exposures. Unfortunately these experiments were relatively unsuccessful. We were unable to fabricate strips of the required materials with adequate uniformity. The fabrication requirements were shown to be clearly beyond the scope and resources of the project. In addition, subsequent developments, to be described, made this modality less significant.

A series of experiments were carried out to test the feasibility of energy-selective radiography without the burden of film considerations. Under support primarily from NSF, NIH and G.E., an elaborate line-scanned x-ray system was acquired which allowed us to acquire x-ray data at different energies in digital form. An x-ray generator was modified to provide rapid energy-switching so that patients could be studied. An associated computer, display and hard-copy printer enabled us to make unique selective-material images. The results of this study are described in Appendix C, "Generalized Image Combinations in Dual KVP Digital Radiography." These studies confirmed the significance of selective material imaging in clinical radiology. Chest images devoid of bone or soft tissue showed remarkable visibility of hidden structures such as airways. In addition, the noninvasive visualization of vessels

and kidneys was greatly improved.

These studies were made on a very high-priced, non-standard instrument. They did strongly indicate, however, that a properly designed spatial-frequency encoding system using conventional radiographic film, followed by a film scanner, would represent a major contribution to diagnosis at a reasonable cost.

The film encoding using the lead grating represents a relatively severe resolution limitation since the low-resolution scintillating screen must resolve the grating. In the course of our studies, a new system was devised using an optical grating positioned between the scintillating screen and the film emulsion. In this system, because of the relatively high bandwidth of the film compared to that of the screen, the encoding process presents no limitation on the system resolution. Also, since all x-ray photons are allowed to hit the screen, the dose considerations are the same as that of a normal study. This system is described in Appendix D, a portion of the Ph.D. Dissertation of Dr. Bruno Strul. A patent application has been prepared on this new system.

In addition to the isolation of iodine, our experimental studies also included the important topic of the separation of bone and soft tissue. This was first done by making measurements using a single beam as described in Appendix E, "Measurement of Soft Tissue Overlying Bone Using Broad Band Energy Spectrum Techniques." In this non-imaging study it was confirmed that the desired information was available for the separation of bone and soft tissue. An experimental study involving the spatial-frequency encoding of bone and plastic is described in Appendix F, a portion of the Ph.D. Dissertation of Dr. Pen-Shu Yeh.

ANALYTIC STUDIES

A number of analytic studies were performed on the information theory considerations of selective material imaging. These concentrated mainly on the problem of the optimum choice of spectral energies and the signal to noise ratio consideration. These are presented in the Appendixes listed below:

Appendix G -- "Applications of Filtered Bremsstrahlung Spectra in Radiologic Studies, Part I: Spectrum Properties and Optimal Energies"

Appendix H -- "Applications of Filtered Bremsstrahlung Spectra in Radiographic Studies, Part II: Measurements of Iodine in Tissue and Separation of Bone and Water"

Appendix I -- "Iodine Imaging Using Spectral Analysis"

Appendix J -- "Noise Analysis in Isolation of Iodine Using Three Energies"

One of the more serious limitations to the accuracy of these techniques is that of scatter. Compton scatter represents a noise source which can often exceed the desired signal. The scatter is strongly dependent on the geometry of the data acquisition system. A study of scatter is included in Appendix K -- "Energy Spectral Analysis in Projection Radiography". In many of these analytic studies listed, extensive experimental verification was performed as indicated in the papers.

CONCLUSIONS

The most significant conclusion of these studies is that selective material imaging using multiple-energy measurements represents a profound improvement in clinical diagnosis. The confirmation of the clinical results was made primarily on a special line-scan system adapted for multi-

spectral imaging. This line-scan system essentially established the technical feasibility and clinical significance of the various techniques.

The line-scan system is a relatively expensive instrument and is well outside the area of conventional radiographic equipment. In our analytical and experimental studies of spatial-frequency encoding we showed that comparable data can be acquired on conventional radiographic film using conventional radiographic equipment. A system was devised for acquiring this data without any loss in resolution. Thus a structure was formulated for providing the desired selective-material imaging within the structure and economics of conventional radiology.

APPENDICES

- A. "Selective Material X-Ray Imaging Using Spatial Frequency Multiplexing"
- B. "Isolated Iodine Images Using Spatial-Frequency Encoding"
- C. "Generalized Image Combinations in Dual KVP Digital Radiography"
- D. "Scatter Considerations in Diagnostic Radiology"
- E. "Measurement of Soft Tissue Overlying Bone Utilizing Broad Band Energy Spectrum Techniques"
- F. "Bone and Tissue Separation on Radiographic Film"
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- K. "Energy Spectral Analysis in Projection Radiography"